

A DECENTRALIZED ADAPTIVE APPROACH TO FAULT TOLERANT FLIGHT CONTROL

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Abstract: This paper briefly reports some results of our study on the application of a decentralized adaptive control approach to a 6 DOF nonlinear aircraft model. The simulation results showed the potential of using this approach to achieve fault tolerant control. Based on this observation and some analysis, the paper proposes a multiple channel adaptive control scheme that makes use of the functionally redundant actuating and sensing capabilities in the model, and explains how to implement the scheme to tolerate actuator and sensor failures. The conditions, under which the scheme is applicable, are stated in the paper.

Keywords: Decentralized flight control, fault tolerance, adaptive control.

1. INTRODUCTION

In applications where a system is expected to track a variety of reference trajectories, use of adaptive control becomes highly desirable. This is the case with highly maneuverable aircraft. In addition, one of the most thorny issues facing control engineers is the lack of an accurate model based on which a feedback compensation strategy necessary to guarantee the system performance is devised. The situation becomes more prominent when failures occur during a system operation such as that encountered by aircraft in a flight mission. Two approaches have been attempted to deal with the latter situation. One approach begins with a process of detecting and identifying parameter changes or faulty subsystems, which is then followed by a process of adjusting the control law. This approach sometimes suffers from high risk and low speed, attributed mainly to the detection and identification process. An alternative is to use adaptive control (Ahmed, et al., 1991; Bodson, et al., 1997; Chandler, et al., 1995; &

Saeks, 1998). The reader is referred to Bodson (1997) for an overview of this approach to fault tolerant flight control. It is claimed in Saeks, Neidhoefer, Cox, and Rap (1998), with little analysis, that by using a multivariate variant of the Seraji (1989) decentralized adaptive control, originally developed for applications in the field of robotics, the following features can be attained: the design of a flight control law requires very little a priori knowledge of the plant dynamics; the implementation of the control law is straightforward; no explicit plant model identification is needed during adaptation; and the asymptotic stability of the flight control system is guaranteed. These all appear to be highly desirable for fault tolerance in flight control.

In order to determine the ability of the decentralized adaptive control (Seraji, 1989) in handling initially poorly known aircraft models, especially aircraft models subject to changes due to unanticipated adverse operating conditions, and to assess the need for involving additional learning schemes such as neural networks, a study was conducted recently by Nikulin and Wu (1999), and Heimes (1999) using the NASA-Dryden 19-state nonlinear aircraft model (Brumbaugh, 1994) as the testbed.

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The model includes full envelope aerodynamics, propulsion system dynamics, actuator dynamics, and atmospheric model, for which a decentralized adaptive control law was attempted. The results of our study is reported briefly in Section 2. In Section 3, a multiple channel configuration is proposed for enhancing fault tolerance of the flight control system.

2. DECENTRALIZED ADAPTIVE CONTROL

There are five control inputs (aileron, symmetric stabilator, differential stabilator, rudder, and thrust) and nineteen measured states in the NASA-Dryden model (Brumbaugh, 1994). The model can be represented by a nonlinear state equation

$$\dot{x} = f(x, u)$$

Our discussion on applying the Seraji control law will be focused on the linearized model of the form

$$\dot{x} = Ax + Bu, \quad y = Cx \quad (1)$$

at a particular operating condition. Since the Seraji control law is performance-based (as opposed to model-based), its dependence on the model fidelity is much less critical. The consideration on the effect of nonlinearity over the entire operational envelope will be given at a later point.

The Seraji control law, being fully decentralized, requires a one-to-one correspondence between the inputs and the outputs. Therefore, the dimension of y must be chosen to be equal to the dimension of u . Suppose $\dim(y) = \dim(u) = m$. The transfer function description of the linearized model is given by

$$Y(s) = C[sI - A]^{-1}BU(s) = \frac{N(s)}{d(s)}U(s)$$

where d is a monic polynomial of degree ν , and N is an $m \times m$ polynomial matrix. Consider s as a differential operator, which leads to the final form of what we call a design model

$$d(s)y(t) = N(s)u(t) \equiv T(t). \quad (2)$$

The design objective is to determine the control law u so that the asymptotic tracking of a selected set y of the measured states to a specified class of reference $\{y_{ref}\}$ is achieved. The design model must be chosen carefully to satisfy the following properties.

- (a) y must have the same dimension as u . This is a constraint imposed by using the Saraji decentralized approach.
- (b) All interested, and potentially unstable states

must be observable from y . This is a basic requirement on feedback variables of all control systems. (c) The transfer function from u to y must be minimum phase, i.e., $N^{-1}(s)$ must be a stable transfer matrix. This will guarantee that the transformation from the fictitious control signal T to the actual control signal u is through a stable filter.

Let τ denote one of the components of T , μ denote the corresponding component in y , and $e = \mu_{ref} - \mu$ is the corresponding tracking error. Then we have the following.

Theorem 1. The decentralized control law for (2) in one channel is given by

$$\tau(t) = f(i) + \sum_{i=0}^{\nu-1} k_i(t)e^{(i)}(t) + \sum_{i=0}^{\nu} q_i(t)\mu_{ref}^{(i)}(t). \quad (3)$$

The auxiliary signal f , feedback gains k_i 's, and feedforward gains q_i 's are governed by the following equations

$$\dot{f} = \delta r + \rho \dot{r} \quad (4)$$

$$\dot{k}_i = \alpha_i(re^{(i)}) + \beta_i(re^{(i)})^{(1)} \quad (5)$$

$$\dot{q}_i = \gamma_i(r\mu_{ref}^{(i)}) + \lambda_i(r\mu_{ref}^{(i)})^{(1)} \quad (6)$$

where δ , α_i , and γ_i are positive constants, ρ , β_i and λ_i are nonnegative constants, and

$$r = p_{\nu 1}e + \dots + p_{\nu \nu}e^{(\nu-1)}. \quad (7)$$

$p_{\nu 1}$ through $p_{\nu \nu}$ are from the last row of the solution P of the Lyapunov equation

$$A_F^T P + P A_F + Q = 0, \quad Q = \text{diag}\{\kappa_1, \dots, \kappa_\nu\} > 0. \quad (8)$$

A_F comes from the controller canonical realization (A_F, B_F, C_F) of a desired ν th order stable reference error filter, and positive numbers $\kappa_1, \kappa_2, \dots, \kappa_\nu$ must be chosen so that $p_{\nu i} \geq 0 \forall i$, and $p_{\nu 1} > 0$. The control law given by (3) through (6) ensures asymptotic reference tracking provided that μ and its first $\nu-1$ derivatives are slow signals relative to the auxiliary signal f . When this condition is not satisfied, an additional constraint must be imposed in order to guarantee the asymptotic tracking. The constraint is given by

$$\mu_d(t)[\mu_d(t) - f(0) - \delta \int_0^t r(\sigma) d\sigma] < -\frac{\delta}{2} \dot{V}_0(t), \quad \forall t, \quad (9)$$

where

$$\mu_d(t) = [d(s) - s^\nu]\mu(t)$$

and $\dot{V}_0(t)$ is the derivative of the Lyapunov function used to derive the adaptation gains with $\mu_d(t)$ set to zero, given by

$$\dot{V}_0(t) = -\epsilon' Q \epsilon - 2r^2[\rho + \sum_{i=1}^{\nu} \beta_i(e^{(\nu-1)})^2 + \sum_{i=0}^{\nu} \lambda_i(\mu_{ref}^{(i)})^2].$$

Vector ϵ in the above expression is given by

$$\epsilon = [e - e_m \quad (e - e_m)^{(1)} \quad \dots \quad (e - e_m)^{(\nu-1)}]'$$

where e_m is the state of the desired ν th order stable reference error filter (A_F, B_F, C_F) . \square

The proof of this theorem draws heavily from the work of Seraji (1989). The modification of the Seraji control law to the current form (3)-(6) was suggested in Saeks (1998), where neither a proof nor conditions (7)-(9) were given. Since our proof for Theorem 1 is rather long, it is not included in this paper. The details of the proof will be provided upon request.

Our design of the decentralized adaptive control law for the NASA-Dryden model was successful. With the aid of a differential evolution strategy (Heimes, 1999) we are able to determine a single set of parameters in the adaptation laws (3)-(6) for all five flight conditions listed in Table 1. On the other hand, the design is by no means a straightforward matter. Many practical issues must be dealt with. The rest of the section is focused on discussing some of the issues: the model fidelity issue, the reference model issue, and the high order derivative issue.

Fl. cond.	Altitude(ft)	Mach	Airspeed(ft/s)
# 1	17900	0.62	650
# 2	9800	0.5	540
# 3	39800	0.6	580
# 4	39800	1.4	1355
# 5	9800	0.9	973

Table 1

(A) Model fidelity. It can be seen that, besides the degree of $d(s)$, no other information about $d(s)$ or $N(s)$ is required to obtain control law (3). $T(s)$, however, is only a fictitious control signal that cannot be applied to the aircraft. One must have the full information on N , in order to calculate the real control signals

$$u(s) = N^{-1}(s)T(s). \quad (10)$$

On the other hand, when the above input is applied

$$y(s) = \frac{N(s)}{d(s)} N^{-1}(s)T(s) = \frac{I}{d(s)} T(s)$$

as if T were directly applied to plant $I/d(s)$. Unfortunately, filter $N^{-1}(s)$ that comes from the design model generally does not match the $N^{-1}(s)$ part of the true plant model. To distinguish a design model from a true model, subscript "D (design)" and subscript "T (true)" will be used wherever appropriate. One source of mismatch between $N_D^{-1}(s)$ and $N_T^{-1}(s)$ is that the current system operating point may be different from the one

at which the linearized design model is extracted. The severity of mismatch varies from point to point within the operational envelope. Therefore, $N_D^{-1}(s)$, when cascaded to the input of the plant, introduces extra poles and cross-channel couplings because $N_T(s)N_D^{-1}(s) \neq I$. For the NASA-Dryden model, $N_D^{-1}(s)$ is an extremely slow filter that it has a settling time of approximately 400 sec., which dominates the response of the system. To overcome this problem, we replaced low pass filter $N_D^{-1}(s)$ by all pass filter $N_D^{-1}(0)$. In doing so the residual signal $[N_D^{-1}(s) - N_D^{-1}(0)]T(s)$ is ignored, in addition to the above mentioned mismatch. The residual signal is generally a fast signal containing the high frequency components of T , and thus easily violates the condition of Theorem 1. To satisfy the sufficient condition for Lyapunov asymptotical stability, a term $-\sigma_i k_i$ can be added to the right hand side of (5), called a σ -modification (Ioannou, 1986), as a more practical alternative to verifying inequality (9). As a result, a residual tracking error in the order of $\sqrt{\sigma}$ is introduced. Cushioned by the sufficiency of the Lyapunov stability theorem, the control system can sometimes be spared of instability without having to take this extra step, as we have observed in our design. However, our freedom in choosing parameters δ , ρ , α_i , \dots in adaptation laws (4)-(6) becomes severely restricted. Suppose the extra step has been taken to guarantee the Lyapunov asymptotic stability, $u(t)$ can be solved from

$$N_D(0)u(t) \equiv T(t)$$

The above equation can be regarded as an effort to scale the fictitious control signals to the dimensions of the real input signals. Through the above equation cross channel coupling is reintroduced.

(B) Reference models. Much effort goes into the selection of the reference models (Heimes, 1999). The speed control reference model, lateral axis reference model, and longitudinal axis reference model are all selected to be sufficiently conservative to allow a single set of parameters in the adaptive control law to work for all flight conditions, and yet sufficiently aggressive to allow a reasonable aircraft tracking performance.

(C) High order derivatives. Because of the way the problem is formulated, high order derivatives with respect to the tracking error and reference signals enter the control law (3). Though derivative terms are desirable for improving the transient performance, by nature they are difficult to be calculated accurately and they tend to amplify the noises. The extra room provided by the Lyapunov theory allows us to settle with a design that uses up to the third order derivative in any control channel, though the NASA-Dryden model could

potentially lead to a 19th order derivative of the tracking error and of the reference signal in the control law.

3. FAULT-TOLERANCE CONSIDERATION

Our ultimate interest lies with the potential fault-tolerant capability of the decentralized adaptive control law. From the analysis in the previous section, the mild requirement on model fidelity of the Seraji control law motivates us to investigate the degree a control law can extend its authority in a secondary axis when loss of control effectiveness occurs in that axis. For example, the ailerons and the stabilators in the NASA-Dryden model can be made to provide redundant control authorities in the roll, and the rudder and the engines can be made to provide redundant control authorities in the yaw axis. System instability, reduced maneuverability, and cross-coupling are among the consequences of sensor/actuator failures and control surface damage (Bodson, 1997). Therefore, it is important that a multivariate approach be taken to take advantage of the existing functional redundancy.

Fig.1 shows the measured roll/yaw rates and the control signals of a simulated scenario—a coordinated turn, carried out at an altitude of 17900 ft and an airspeed of 650 ft/sec using the stabilators and the rudder of the NASA-Dryden model. The decentralized adaptive control described in the previous section is used. Fig.2 shows the same set of signals resulting from the same maneuver at the same flight condition. This time however, an 80% loss of right stabilator effectiveness is simulated. In this case, only the auxiliary control signal (4) is applied, which represents the conventional portion of the adaptive control law (4)-(6). It can be seen that the aircraft performance is severely degraded. After turning on the adaptive control law, as shown in Fig.3, the system is able to maintain the trim and restore the tracking under the failure condition. It is also observed (but not shown in the plots) that the side slip angle in this situation is kept within the prescribed limit of $\pm 2^\circ$. The auxiliary signal, and the adaptation gains for the roll rate tracking error and the roll rate reference signal are shown in Fig.4. This indicates that with adequate redundancy in the plant it is possible to design an adaptive control law that tolerates severe adverse conditions. The rest of the paper devotes to exploring such potentiality through a new fault tolerant configuration that requires a minimum local monitoring effort at the sensors and the actuators. Investigation is on going to implement the new configuration through simulations. Fig.1 through Fig.4 are all shown in the last page of the paper.

Suppose a *design* model at a particular operating point takes the form

$$\dot{x} = Ax + B_1u_1 + B_2u_2, \quad y_1 = C_1x, \quad y_2 = C_2x \quad (11)$$

where $x \in R^n$, $u_1 \in R^{m_1}$, $u_2 \in R^{m_2}$, $y_1 \in R^{m_1}$, and $y_2 \in R^{m_2}$. Typically in this kind of applications $m_1 = m_2 = 3$. The division of the inputs is based on the result of an analysis so that each u_i can provide adequate full control authority, which requires sufficient controllability of (A, B_i) . y_1 and y_2 are two alternatives, each adequately reflecting the requirements on the tracking performance, which requires sufficient observability of (C_i, A) . A combined measure of controllability and observability, called by Wu, Zhou, and Salomon (2000) a reconfigurability, should be imposed. More than two sets of inputs and outputs should be considered whenever the redundancy allows. In addition, the input to output transfer matrix defined by (variable s is suppressed)

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \frac{\begin{bmatrix} N_{11} & N_{12} \\ N_{21} & N_{22} \end{bmatrix}}{d} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \frac{N}{d} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \quad (12)$$

is a minimum phase system, i.e., $N^{-1}(s)$ is a stable transfer matrix. We also require that $N_{ii}^{-1}(s)$'s are stable transfer matrices. $d(s)$ is a monic polynomial of degree ν in s , $N(s)$, and $N_{ij}(s)$'s are $m_1 + m_2 \times m_1 + m_2$, and $m_i \times m_j$ polynomial matrices, respectively, of degrees less than ν . Again consider s as a differential operator, and define the design model

$$d(s)y_1(t) = N_{11}(s)u_1(t) + N_{12}(s)u_2(t) \equiv T_1(t) \quad (13)$$

$$d(s)y_2(t) = N_{21}(s)u_1(t) + N_{22}(s)u_2(t) \equiv T_2(t) \quad (14)$$

We are now in a position to state the asymptotic tracking problem. Determine T_1 and T_2 so that

$$y_1(t) \xrightarrow{t \rightarrow \infty} y_{1ref}, \text{ and } y_2(t) \xrightarrow{t \rightarrow \infty} y_{2ref}. \quad (15)$$

Obviously, if T_1 and T_2 can be produced satisfactorily, u_1 and u_2 can be obtained by sending T_1 and T_2 through the stable filter $N^{-1}(s)$. Moreover, the individual components of y_i and those of T_i have one to one correspondence.

Theorem 2. Suppose T_1 and T_2 in (13) and (14) solve the asymptotic tracking problem. When some of the components of y_i become unavailable ($= 0$), control law T_j , $j \neq i$ solves the asymptotic tracking problem. When some of the components of u_i become unavailable ($= 0$), control law $u_j = N_{jj}^{-1}T_j$, $j \neq i$ solves the asymptotic tracking problem.

Proof. Suppose some components of y_i are no longer available. From (3) it is seen that T_j , $j \neq i$ depends only on y_j and y_{jref} . Therefore $y_j \rightarrow$

y_{jref} , provided that (9) is satisfied for design model $d(s)y_j(t) = T_j(t)$. Since y_j has been selected to reflect the tracking requirement, T_j solves the asymptotic tracking problem. Suppose now that u_i becomes unavailable.

$$T_j = N_{ij}u_i + N_{jj}u_j = N_{jj}u_j.$$

Again T_j , $j \neq i$ solves the asymptotic tracking problem, i.e., $y_j \rightarrow y_{jref}$, provided that (9) is satisfied for design model $d(s)y_j(t) = T_j(t)$. Since $u_j(s) = N_{jj}^{-1}(s)T_j(s)$, and N_{jj}^{-1} is stable, u_j solves the asymptotic tracking problem. \square

Note that if model fidelity is an issue, σ -modification (Ioannou, 1986) may be required in order to achieve asymptotic tracking. Fig.3 shows one implementation among many possible implementations of the multiple channel configuration. This implementation requires the local monitoring of sensors and actuators, which is a much less demanding task than the task of diagnosis. In this setup, when measurement y_1 , or input u_1 becomes faulty, filter N_{11}^{-1} is set to zero. When measurement y_1 , or input u_1 becomes faulty, filter $(N_{22} - N_{21}N_{11}^{-1}N_{12})^{-1}$ is set to zero. In general however, no reconfiguration is required as long as the remaining control input set contains at least all components of u_i , or that the remaining measurement set contains at least all components of y_i , in addition to satisfying the conditions of Theorem 1.

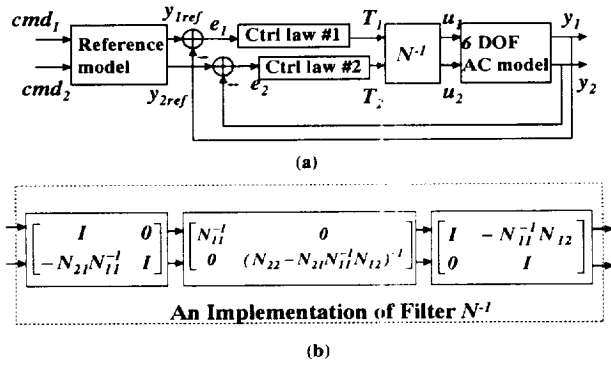


Fig.5 A multi-channel configuration

Normally a better tracking performance can be expected if the parameters in the adaptation law (4)-(6) are scheduled for different flight conditions (Nikulin and Wu, 1999). When information is available, the parameters of filter N^{-1} can also be scheduled. In that case, the single filter in Fig.5 is replaced by a bank of filters scheduled for various flight conditions.

4. CONCLUSIONS

This paper presents some results of our initial investigation on the feasibility to extend a decen-

tralized adaptive control scheme (Seraji, 1989) to flight control. Such an extension is suggested in Saeks (1998). The paper examines the conditions under which the decentralized adaptive control can be applied, and explicitly implements such a decentralized adaptive control law on the NASA-Dryden model (Brumbaugh, 1994). Though the analysis presented in the paper validates the decentralized control law, there is no easily checkable conditions for guaranteeing the asymptotic tracking. Therefore, extensive simulation plays a very important role in ensuring a successful design. Our simulation and analysis results have shown the promise of the method in handling severe aircraft impairment, and severe under modeling. Based on this observation, a multiple channel configuration is proposed for achieving fault-tolerance. This configuration requires the implementation of a full scale multivariable design which is being pursued.

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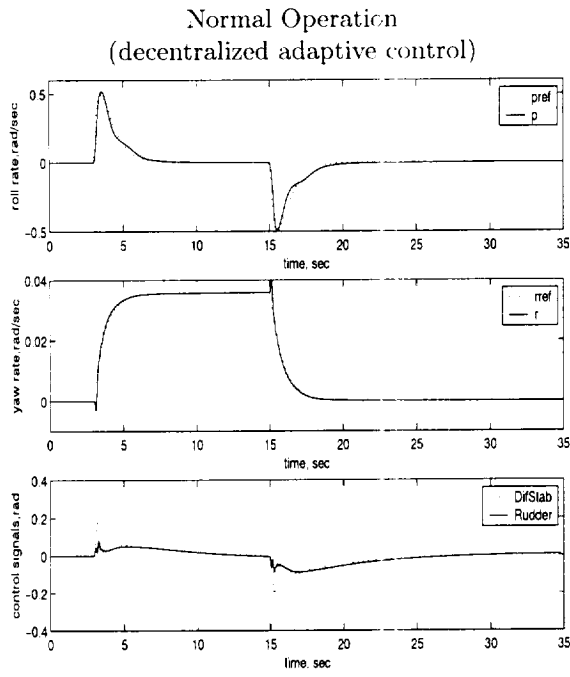


Fig.1 Measured roll/yaw rates and rudder/stabilator control signals

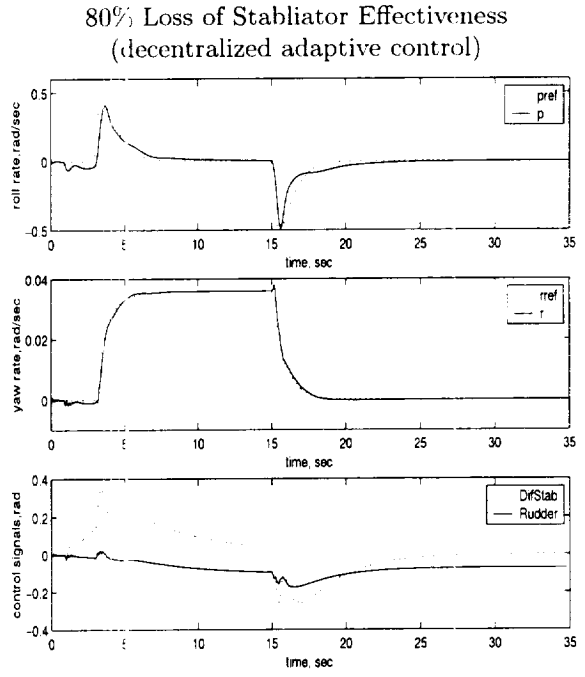


Fig.3 Measured roll/yaw rates and rudder/stabilator control signals

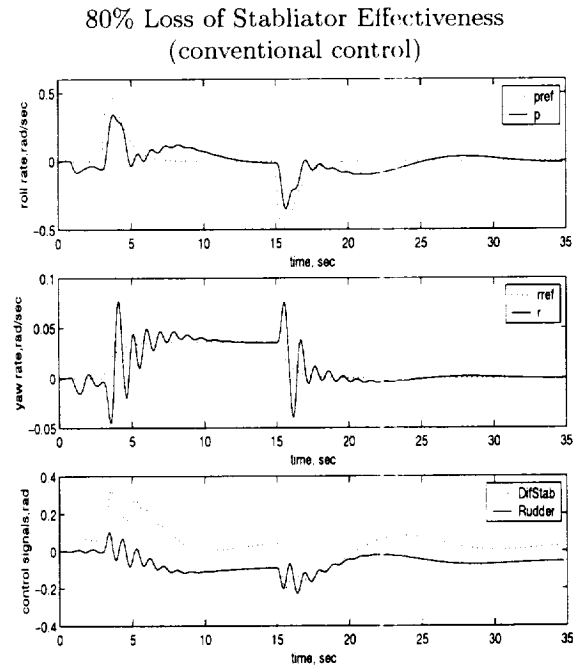


Fig.2 Measured roll/yaw rates and rudder/stabilator control signals

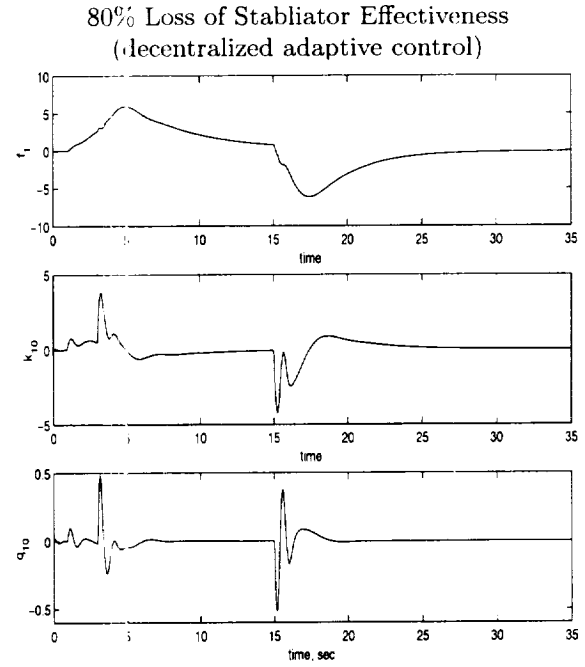


Fig.4 Stabilator auxiliary signal, and leading feedback, and forward adaptation gains